Dynamical Climatology

The equilibrium response to doubling atmospheric CO_2

by

John F.B. Mitchell

DCTN 82

September 1989

Meteorological Office (Met. O. 20)
London Road
Bracknell
Berkshire RG12 2SZ

DYNAMICAL CLIMATOLOGY TECHNICAL NOTE NO. 82

THE EQUILIBRIUM RESPONSE TO DOUBLING ATMOSPHERIC CO_2

by

John F B Mitchell

To appear in Proceedings of "Workshop on Greenhouse Gas Induced Climatic Change: A Critical Appraisal of Simulations and Observations" 8-12 May 1989, University of Massachusetts, Amherst.

Met O 20 (Dynamical Climatology Branch)
Meteorological Office
London Road
Bracknell
Berkshire, UK RG12 2SZ

September 1989

NOTE: This paper has not been published. Permission to quote from it should be obtained from the Assistant Director of the above Meteorological Office branch.

Abstract

1. Introduction

In the last year, there has been an intensification of interest in the climatic effects of increases in greenhouse gasses, partly because of extreme events, including the summer drought in the United States, partly associated with political initiatives such as the Toronto Conference (August 1988). Five Centres, the Geophysical Fluid Dynamics Laboratory (GFDL), the Goddard Institute for Space Studies (GISS), the British Meteorological Office (BMO), the National Centre for Atmospheric Research (NCAR) and Oregon State University (OSU) have recently published details of one (or more) numerical studies of the climatic effects of doubling CO_2. At least four other centres (the Max Planck Institute Hamburg, the Canadian Climate Centre, the Meteorological Research Institute, Japan and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in co-operation with the Bureau of Meteorology in Australia are running, or about to carry out, similar numerical studies, and Institutes in Italy, France and the People's Republic of China have also expressed interest in such work. The Inter-Governmental Panel on Climatic Change (IPCC) is to produce a major assessment of the predictions of climate change to be presented at the World Climate Conference and to the United Nations in late 1990.

Given this rapid acceleration in scientific and political activity, the useful lifetime of a review such as this is limited. Furthermore,

detailed reviews of the topic have been given recently by Dickinson (1986), Schlesinger and Mitchell (1987) and Mitchell (1989). Hence, in this paper, I will summarize much of what has gone before, allowing the reader to refer to previous reviews or the original papers for a more detailed explanation of results obtained to date, and I will attempt to highlight what I believe are the main areas of agreement and disagreement between different studies, and indicate areas where I think that further research is necessary.

2. Equilibrium Experiments with Mixed-Layer Oceans

The thermal relaxation time of the deep ocean is of the order of centuries. Thus, equilibrium experiments with models including the deep ocean are prohibitively expensive. (Bryan (1984)) has derived a method of accelerating the convergence to equilibrium in the absence of the seasonal cycle). Most equilibrium experiments to date have used atmospheric models coupled to an oceanic mixed layer, generally of order 50 metres deep. In early experiments, the advection of heat by the ocean was ignored; in later experiments this is allowed for by prescribing a heat convergence to represent non-local oceanic effects. This heat convergence is assumed not to change with doubling CO_2. The horizontal resolution is generally about 550 km (880 km in the case of the GISS experiments), though experiments at higher resolution are now being carried out (Wetherald, personal communication).

2.1 Temperature

The simulated global mean warming and doubling CO_2 in atmosphere-mixed layer ocean models varies from 1.9K to 5.2K (Figure 1). Cess and Potter (1987) plotted the equilibrium global mean temperature change obtained by doubling CO_2 in five different studies against the global mean temperature in the simulation of present day climate. They noted that the largest warming occurred in the model with the coldest control climate, and vice versa. Although there are plausible explanations why this should be the case (the colder the control, the larger the sea-ice extents and hence the greater positive ice-albedo feedback; the warmer the control, the stronger the negative lapse rate feedback due to the increasing importance of moist processes) the rate of change of sensitivity with temperature suggested by the straight line fit in Figure 1 is far greater than can be explained by such mechanisms. Mitchell and Warrilow (1987) modified the treatment of land surfaces in the Meteorological Office model, increasing the global mean temperature and the control simulations slightly, but without affecting the global mean sensitivity. Cess et al (1989) demonstrated that there are large differences in cloud feedback produced by at least three of the models represented in Figure 1. Mitchell et al (1989) obtained warmings which ranged from 5.2 to 1.9K with versions of the Meteorological Office model with increasingly sophisticated, but not necessarily more accurate, cloud parametrizations. The surface temperature of the control simulation only varied between 287.2 and 287.7K. In

summary, the discrepancies in global mean warming simulated by the different models is too large to be explained in terms of differences in the temperature of the simulated present day climate. The biggest contribution must come from the differences in the parametrizations of physical processes, especially those associated with cloud.

The geographical and seasonal distribution of the warming shows some similarity from model to model. The warming is greatest around sea-ice margins in winter (see for example, Figure 2) and least over sea-ice in summer. The larger winter warming is associated with changes in sea ice (Manabe and Stouffer 1980; Ingram et al, 1989). There is little seasonal variation in the warming of the tropics. The warming is generally greater over land than over the open ocean at similar latitude. The annual mean warming is greatest at high latitudes.

The main relative discrepancies occur in the magnitude of the warming (1) in the tropics throughout the year and (2) over the northern mid-latitude continents in summer. For example, both the GISS (Hansen et al, 1984) and GFDL (Manabe and Wetherald, 1987) models produce a global mean warming of about 4K. However, the GISS model produces a larger warming in the tropics and a smaller warming at high latitudes (Figure 3). The GISS model produces a much larger warming in the upper tropical troposphere (up to 8K compared with 4K in the case of the GFDL experiment, see Figure 4). This discrepancy may be related to the convective

parametrization. The GISS results are qualitatively similar to those attained with the BMO model (Wilson and Mitchell, 1987), which uses a similar penetrative convection scheme. The GFDL results are more like those obtained with the NCAR model (Washington and Meehl, 1984) which uses an equivalent moist convective adjustment parametrization. However, an attempt to confirm that a penetrative scheme would produce a greater warming in the tropics has proved inconclusive (Cunnington and Mitchell 1989).

The GFDL and BMO models produce a relatively large warming over the northern mid-latitude continents in summer. This is associated with the drying of the land surface (Manabe et al, 1981). On the other hand, the NCAR (and to a lesser extent, the GISS) model produces a wetter land surface for much of this region in summer, so that enhanced evaporation occurs at the expense of a smaller surface warming (See for example, Figure 2).

2.2 Precipitation

The range of intensification in the hydrological cycle varies from 4% to 15%. The size of the intensification is largely dependent on the size of the warming (Figure 5). This is to be expected, given the increase in saturated vapour pressure with temperature. However, the rate of increase is typically less than half that given by the Clausius Clapeyron relation (about 6%/K at 288K), and

appears to be limited by energy budget considerations (Mitchell et al, 1987).

There is some agreement on patterns of the larger scale features in the changes in precipitation. All models produced enhanced precipitation in high latitudes on doubling CO_2 associated with enhanced moisture convergence (Manabe and Wetherald, 1975; Mitchell, 1983) and in the tropics, and in mid-latitudes in winter (see for example Figure 6). Changes in the subtropics are generally small, with both increases and decreases.

There is, however, considerable disagreement on smaller scales, especially over the northern continents in summer and in the tropics. A number of GFDL and BMO simulations, along with that from OSU, suggest a reduction in precipitation over much of the northern mid-latitude continents in summer (particularly in the GFDL models) and an enhancement of the Asian south west monsoon. In general, the precipitation in the intertropical convergence zone (ITCZ) is enhanced, and there is a tendency for a tropical precipitation maximum to shift into the summer hemisphere. This may be associated with a strong positive cloud feedback in the summer hemisphere (Wilson and Mitchell, 1987). In contrast, the GISS (Hansen et al, 1984) and particularly the NCAR (Washington and Meehl, 1984) models produce a widespread increase in precipitation over the northern mid-latitude continents in summer, and in the case of the GISS model, a tendency for the ITCZ to shift towards the winter hemisphere. As a result, there is little

or no consensus on the equilibrium changes in precipitation in the tropics, or over the northern mid latitudes in summer.

2.3 Soil Moisture

One of the major controversies arising from the studies made to date concerns whether or not the surface of the northern mid-latitude continents will become drier in summer. The bulk of the northern continents become wetter in winter in all simulations because of the enhanced winter precipitation, and the relatively small increase in evaporation found at the low winter temperatures. In summer, all the GFDL and BMO experiments and the OSU study produce a drying of the northern mid-latitude land surface in summer (Figure 7) due to one or both of the following factors: reduced precipitation and enhanced evaporation, the latter following earlier snow melt and/or reduced cloud cover and/or enhanced longwave radiation from the warmer, moister CO_2 enriched atmosphere. The NCAR and GISS models produce a wetter surface (Figure 7). Mitchell and Warrilow (1987) changed the parametrization of run off over frozen ground in a version of the BMO model, demonstrating that where the land surface is far from saturation at the time of spring snow melt in the control simulation, the land surface will remain wetter for much of the spring and summer on doubling CO_2 concentration. Meehl and Washington (1988) reported that the NCAR model produces a very dry land surface throughout the year in its simulation of present day climate (possibly because of the use of a low surface albedo over

land). Hence, the increase in summer soil moisture found in that model is consistent with Mitchell and Warrilow's results. The GISS model uses a parametrization over frozen ground (Hansen et al, 1983) which is similar to that used in the alternative version of the Met Office model. The NCAR results are dubious, given that the simulated soil moisture and runoff in the control simulation are excessively small. The GISS model uses a very coarse horizontal grid (880 km) and so may not represent the weak disturbances associated with summer rainfall adequately. Simulations with GFDL and BMO models at higher (250 km) horizontal resolution consistently produce a drying of the mid latitude surface in summer (Manabe et al, 1981; Mitchell and Lupton, 1984; Wetherald (1989) personal communication). Nevertheless, a 440 km grid version of the GISS model with prescribed changes in sea temperature failed to produce a substantial summer drying on doubling atmospheric CO_2 (Rind, 1987).

In summary, most but not all models produce a drying of the Northern extratropical continents in summer. In those models producing a drying, the mechanisms are well understood and are very plausible.

3. Equilibrium studies with dynamical ocean-atmosphere models.

The use of dynamical ocean atmosphere models in equilibrium 2 x CO_2 simulations has been limited, partly because of the difficulty in bringing the deep ocean to equilibrium. Manabe and Bryan (1984) carried out a series of equilibrium simulations using the low

resolution model with idealised geography and annually averaged insolation. The main characteristics of the atmospheric warming obtained on enhancing CO_2 (Figure 8) is similar to that using mixed layer model, namely a stratospheric cooling, and maximum warming at upper tropospheric levels in the tropics and in high latitudes at the surface. The warming at high latitudes is propogated into the deep ocean at all latitudes. Manabe and Bryan (1985) note that in the warmer climates the thermohaline circulation changes little, as the larger warming and high latitudes is compensated by the smaller coefficient thermal expansion at lower temperatures. Thus the changes in density in high and low latitudes are similar.

No equilibrium studies have been carried out to date with a seasonal cycle and a realistic geography, so as yet it is not possible to say whether or not changes in ocean circulation would substantially alter the patterns of Climate change determined using mixed layer models. Manabe and Stouffer (1988) have demonstrated that coupled models may produce more than one equilibrium, though there is no evidence to suggest that more than one equilibrium may exit for enhanced CO_2 simulation.

4. Summary of results deduced from equilibrium 2 x CO_2 experiments

The following changes are virtually certain to occur on enhancing atmospheric CO_2:

* the stratosphere will cool
* the troposphere will warm
* the global water cycle will be enhanced

The following changes are simulated by all comparable models and will probably occur.

* the warming will be largest in high latitudes in winter
* the annual mean warming is smallest in the tropics
* the warming in the tropics varies little with season
* precipitation increases in mid to high latitudes in winter
* soil moisture and run off all increase in mid to high latitudes of the northern mid-continents in winter.
* seasonal sea-ice melts earlier and forms later.

The following changes are common to some, but not all, models and hence are less certain.

* seasonal snow cover accumulates later and melts earlier
* soil moisture amounts decrease in the northern mid-latitude continents in summer.

The global mean warming at equilibrium varies from 2 to 5K and the enhancement of the water cycle ranges from 4 to 15%. Much of the discrepancy is due to differences in simulated cloud feedback. In general, there is better agreement for simulated changes in temperature than in the hydrological cycle.

5. Priorities for future research to improve atmosphere models

The equilibrium studies carried out so far indicate several areas with the need or potential for improvement. First, there is considerable uncertainty in the estimates of cloud climate feedbacks. Climate models are just beginning to include cloud water content as an explicit variable which will enable an estimate of the feedbacks due to change in cloud radiative properties. Further feedbacks may occur due to changes in cloud droplet distribution. Very little is known about the radiative properties of ice clouds and how they may be represented in large scale models. Secondly, there are large discrepancies in the simulated warming in the tropics which appear to depend in the choice of convection scheme. Third, there is still much to be done in including the effects of vegetation in climate models. It is likely that improvements will have little effect on the global climate sensitivity, but may have pronounced effects at and near the surface, and hence are important for climate impact studies. Fourth, it is evident that increased resolution from the 15 spectral waves or 5° latitude by 8° longitude typical of current models will produce a substantial improvement in the simulation of current climate, particularly hydrology. However, with the current generation of computers, it is unlikely that one can make accurate prediction of the regional effects without resorting to other techniques such as nesting high resolution limited area models over regions of specific interest within global climate models. Finally, current simulations of equilibrium change have not taken into account possible changes in

ocean circulation. Although such changes are unlikely to affect global sensitivity significantly, they may have substantial local effects.

Bryan, K. Accelerating the convergence to equilibrium of ocean-climate models J Phys. Oceanogr. 14(4) 666-673, 1984.

Cess, R.D. and Potter, G.L. Exploratory studies of cloud radiative forcing using a general circulation model. Tellus, 39A, 460-473, 1987.

Cess, R.D. and Potter, G.L. A Methodology for understanding and intercomparing atmospheric feedback processes within general circulation models. J. Geophys Res., 93, 8305-8314, 1988.

Cess, R.D., G.L. Potter, J.P. Blanchet, G.J. Boer, S.J. Ghan, J.T. Kiehl, X-Z Liang, J.F.B. Mitchell, J-J Morcrette, D.A. Randall, M.R. Riches, E. Roeckner, U. Schlese, A. Slingo, K.E. Taylor, W.M. Washington, R.T. Wetherald, I. Yagaii. Intercomparison and interpretation of cloud-climate feedback as produced by thirteen atmospheric general circulation models, Science, 245, 513-516, 1989.

Cunnington, W.M. and Mitchell, J.F.B. On the dependence of climate sensitivity on convective parametrization. Submitted to Climate Dynamics. 1989.

Dickinson, R.E. "How will climate change?" In "The Greenhouse Effect, Climate Change and Ecosystems", Eds. B. Bolin, B.R. Doos, J. Jager and R.A. Warwick, SCOPE 13, Wiley, New York, 206-270. 1986.

Hansen, J., Russell, G., Rind, D., Stone, P., Lacis, A., Lebedeff, S., Ruedy, R., and Travis, L. Efficient three-dimensional global models for climate studies: Models I and II, Month. Wea. Rev. 111, 609-662 (Paper 1). 1983.

Hansen, J., Lacis, A., Rind, D., Russell, L., Stone, P., Fung, I., Ruedy, R., and Lerner, J. Climate Sensitivity and Analysis of Feedback Mechanisms. In Climate Sensivity (ed. J. Hansen and T. Takahashi) Geophysical Monograph 29, 130-163. American Geophysical Union, Washington D.C. 1984.

Ingram, W.J., Wilson, C.A. and Mitchell, J.F.B. Modelling climate change: an assessment of sea-ice and surface albedo feedbacks. J. Geophs Res., 94, 8609-8622, 1989.

Manabe, S. and Bryan, K.Jr. CO_2 - Induced Change in a Coupled Ocean - Atmosphere Model and its Paleoclimatic Implications. J. Geophys. Res 90, C11, 11,689-11,707. 1985.

Manabe, S. and Stouffer, R.J. Two stable equilibria of a coupled ocean-atmosphere Model. J of Climate, 1, 841-866. 1988.

Manabe, S., and Stouffer, R.J. Sensitivity of a global climate model to an increase in the CO_2 concentration in the atmosphere. J. Geophys. Res. 85 5529-5554. 1980.

Manabe, S. and Wetherald, R.T. The effects of doubling the CO_2 concentration on a general circulation model. J. Atmos. Sci. 32 3-15. 975. 1975.

Manabe, S. and Wetherald. R.T. Large scale changes of soil wetness indeed by an increase in atmospheric carbon dioxide. J. Atmos. Sci., 44, 1211-1235. 1987.

Manabe, S. and Wetherald, R.T. and Stouffer R.J. Summer dryness due to an increase of atmospheric CO_2 concentration. Climatic Change 3, 347-385. 1981.

Meehl, G.A. and Washington, W.M. A comparison of soil moisture sensitivity in two global climate models. J. Atmos. Sci, 45, 1476-1492. 1988.

Mitchell, J.F.B. The seasonal response of a general circulation model to changes in CO_2 and sea surface temperament Q.J.R. Met. Soc., 109, 113-152. 1983.

Mitchell, J.F.B. The "Greenhouse" effect and climate change. Reviews of Geophysics, 27, 115-139, 1989.

Mitchell, J.F.B. and Lupton, G. A 4 x CO_2 experiment with prescribed changes in sea temperatures. Progress in Biometeorology, 3, 353-374.

Mitchell, J.F.B. and Warrilow, D.A. Summer dryness in northern mid-latitudes due to increased CO_2 Nature 330, 238-240. 1984.

Mitchell, J.F.B., Wilson, C.A. and Cunnington, W.M. On CO_2 climate sensitivity and model dependence of results. Q.J.R. Meteorol Soc., 113, 293-322. 1987.

Mitchell, J.F.B., Senior, C.A. and Ingram, W.J. CO_2 and Climate: a missing feedback? 1989. Nature, 341, 132-134.

Rind, D. The Doubled CO_2 Climate: The impact of sea surface temperature gradient J.Atmos. Soc., 44, 3235-3268. 1987.

Schlesinger, M.E. and Mitchell, J.F.B. Climate Model Simulations of the equilibrium Climatic response to increased carbon dioxide. Reviews of Geophysics 25, 760-798. 1987.

Schlesinger, M.E. Model projections of the climatic changes induced by increased atmospheric CO_2. In proceedings of NATO Symposium 'Climate and Geo-Sciences'. Louvain-la-Neuve, May 23-27, 1988 (To appear).

Schlesinger, M.E. and Zhao, Z. Seasonal climate changes induced by doubled CO_2 as simulated by the OSU atmospheric GCM/mixed layer model. J. of Climate, 2, 463-499, 1989

Spelman, M.J. and Manabe, S. Influence of Oceanic Heat Transport Upon the Sensitivity of a Model Climate. J. Geophys. Res. 89 571-586, 1984.

Washington, W.M. and Meehl, G.A. Seasonal Cycle Experiment on the Climate Sensitivity Due to a Doubling of CO_2 with an Atmospheric General Circulation Model Coupled to a Simple Mixed Layer Ocean Model. J.Geophys. Res.89 9475-9503. 1984.

Wilson, C.A. and Mitchell J.F.B. A doubled CO_2 Climate Sensitivity experiment with a GCM including a simple ocean. J. Geophys. Res, 92, 13315-13343. 1987.

Figure Captions

1. The global mean change in surface temperature due to doubling atmospheric carbon dioxide simulations as a function of simulated control temperatures.

GFDL	Manabe and Wetherald (1987)
GISS	Hansen et al (1984)
NCAR	Washington and Meehl (1984)
OSU	Schlesinger and Zhao (1989)
BMO	Wilson and Mitchell (1987)
M1,M2,M3	Mitchell et al (1989)

2. Simulated change in surface air temperature due to doubling atmospheric CO_2 concentrations during northern summer (June to August). Contours every 2K, stippled where greater than 4K.

a. a GFDL model (Manabe and Wetherald, 1987)

b. an NCAR model (Washington and Meehl, 1984)

3. Changes in zonally averaged annual mean surface temperature due to doubling atmospheric CO_2 from different models. Wetherald (personal communication).

GFDL - Manabe and Wetherald (1987)
GISS - Hansen et al (1984)
NCAR - Washington and Meehl (1984)
BMO - Wilson and Mitchell (1987)

4. Change in zonally averaged atmospheric temperature due to doubling atmospheric CO_2. (June to August). Contours every 1k, areas of decrease stippled.

a. a GFDL model (Manabe and Wetharald, 1987)
b. a GISS model (Hansen et al, 1984)

5. Percentage increase in precipitation as a function of simulated warming due to doubling atmospheric CO_2. (Labelled as in Figure 1).

6. Simulated change in precipitation due to doubling atmospheric CO_2. Contours at 0, +-1, +-2 midday. Areas of decrease are stippled.

a. December to February
b. June to August

7. Simulated changes in soil moisture (June to August) due to doubling atmospheric CO_2, from 5 different models.

GFDL	Manabe and Wetherald (1987)
GISS	Hansen et al (1984)
NCAR	Washington and Meehl (1984)
OSU	Schlesinger and Zhao (1989)
BMO	Wilson and Mitchell (1987)

Areas of decrease are stippled. Note that the contour interval varies. (from Schlesinger, 1989).

8. Height latitude diagram of zonally averaged equilibrium changes in temperature due to quadrupling CO_2 in an idealized coupled ocean-atmosphere model. (From Spelman and Manabe, 1984) Conours at -8K, -4K, -1K and then every 1K upwards. Extra contours at 3.5K and 6.5K. Areas of decrease lightly stippled, and warming greater than 7K is heavily stippled.

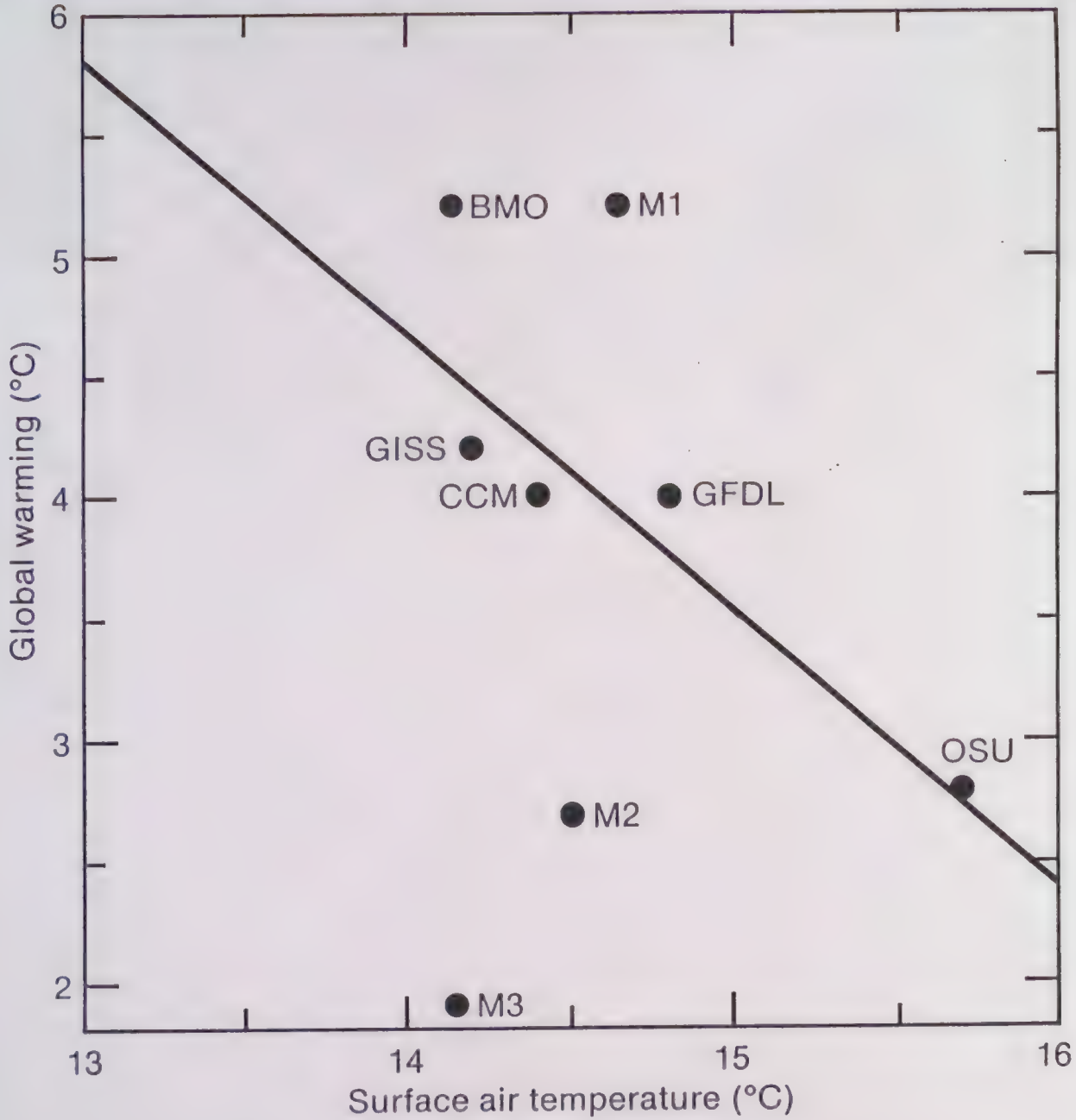
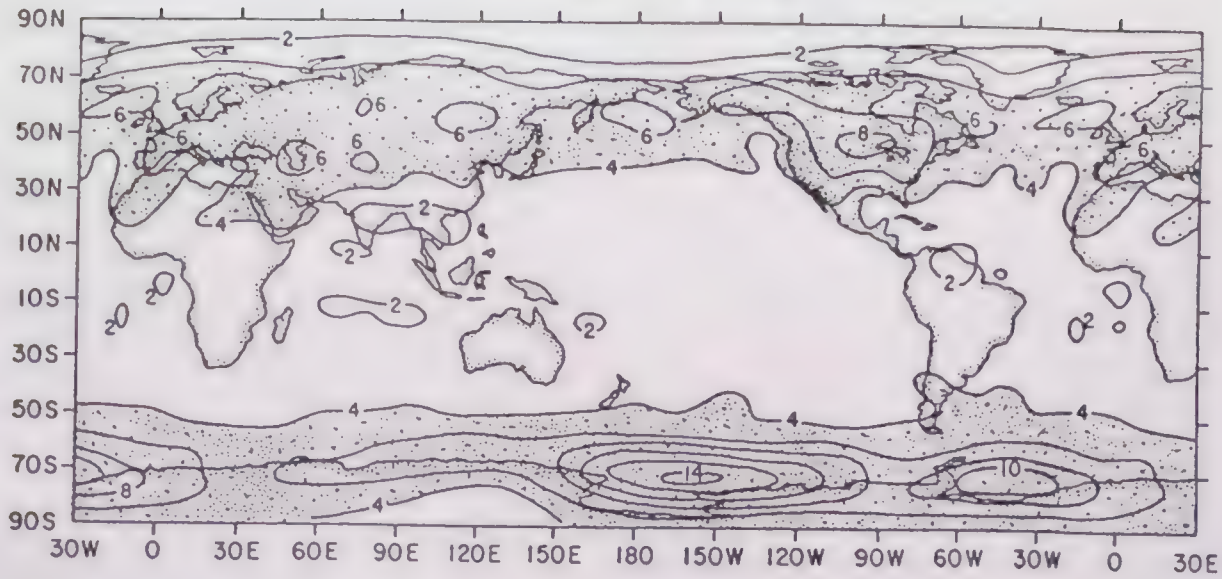


FIGURE 1

The temperature for BMO has been corrected from 13.7 to 14.3°C, to allow for averaging over the diurnal cycle.

TEMPERATURE DIFFERENCES FOR JJA

GFDL, $2\times CO_2 - 1\times CO_2$



NCAR, $2\times CO_2 - 1\times CO_2$

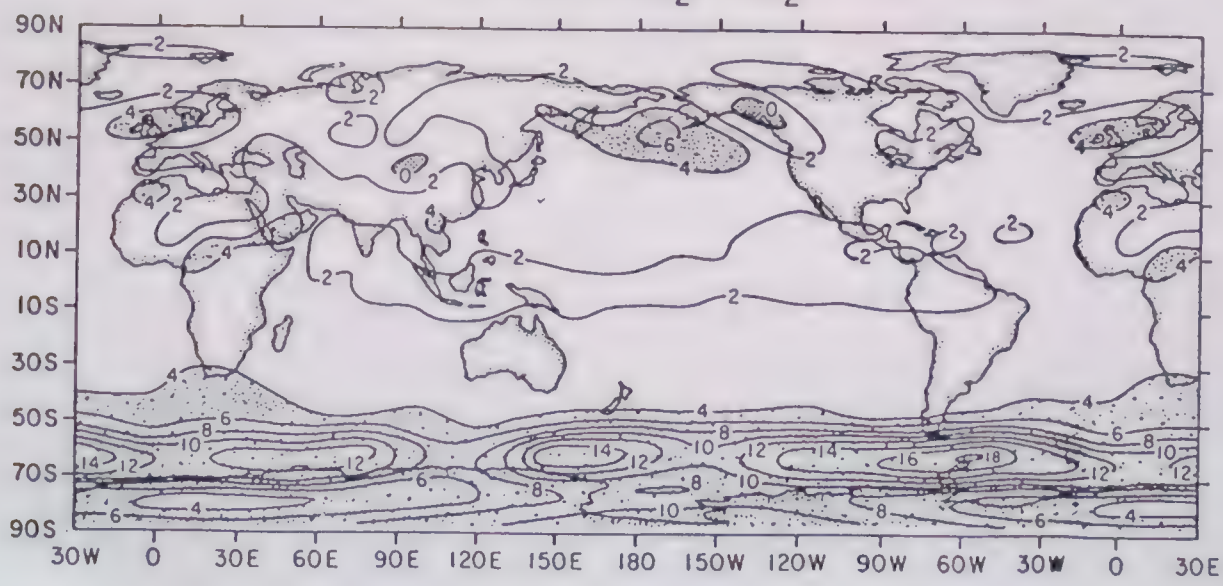


FIGURE 2

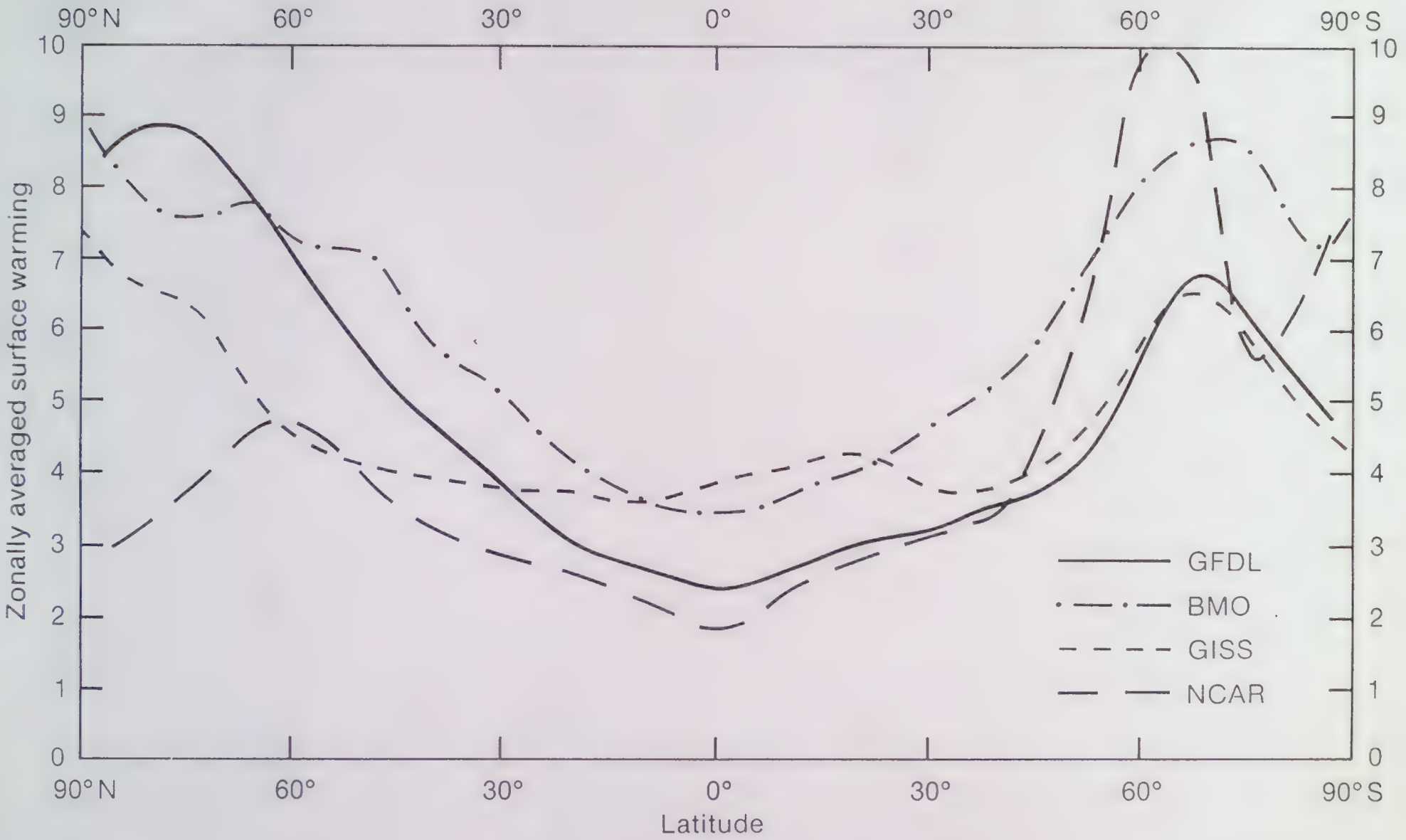

90° N
60°
30°
0°
30°
60°
90° S
10
9
8
7
6
5
4
3
2
1
0
Zonally averaged surface warming
GFDL
BMO
GISS
NCAR
Latitude

FIGURE 3

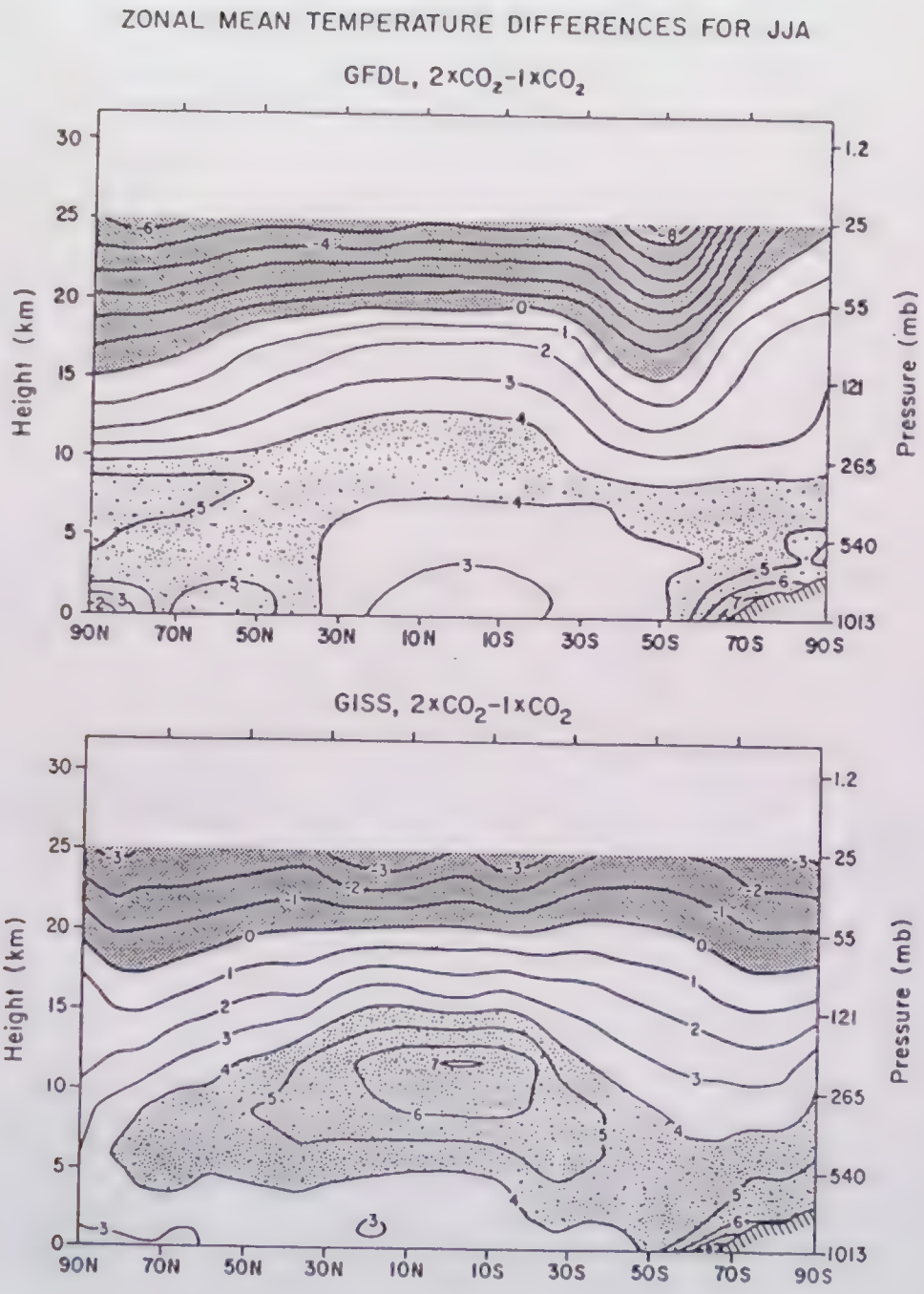

ZONAL MEAN TEMPERATURE DIFFERENCES FOR JJA
GFDL, 2×CO2-1×CO2
Height (km)
Pressure (mb)
30
25
20
15
10
5
0
1.2
25
55
121
265
540
1013
90N
70N
50N
30N
10N
10S
30S
50S
70S
90S
GISS, 2×CO2-1×CO2
Height (km)
Pressure (mb)

FIGURE 4

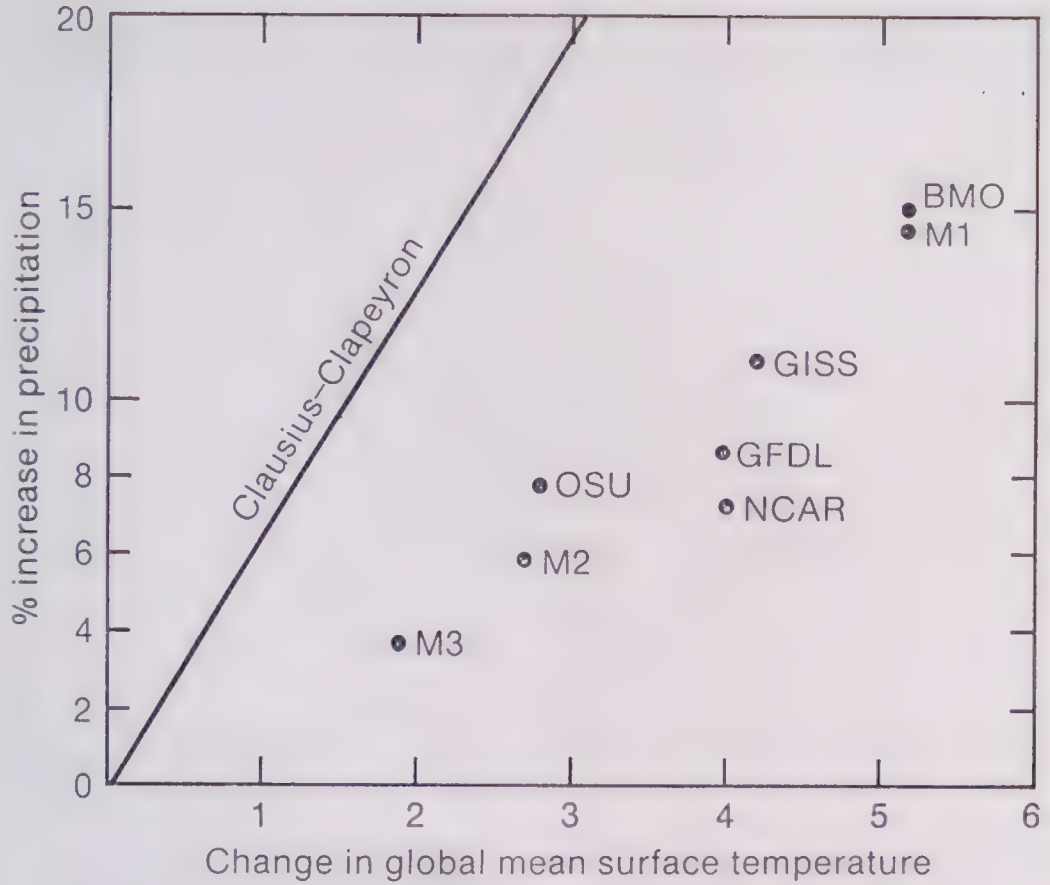
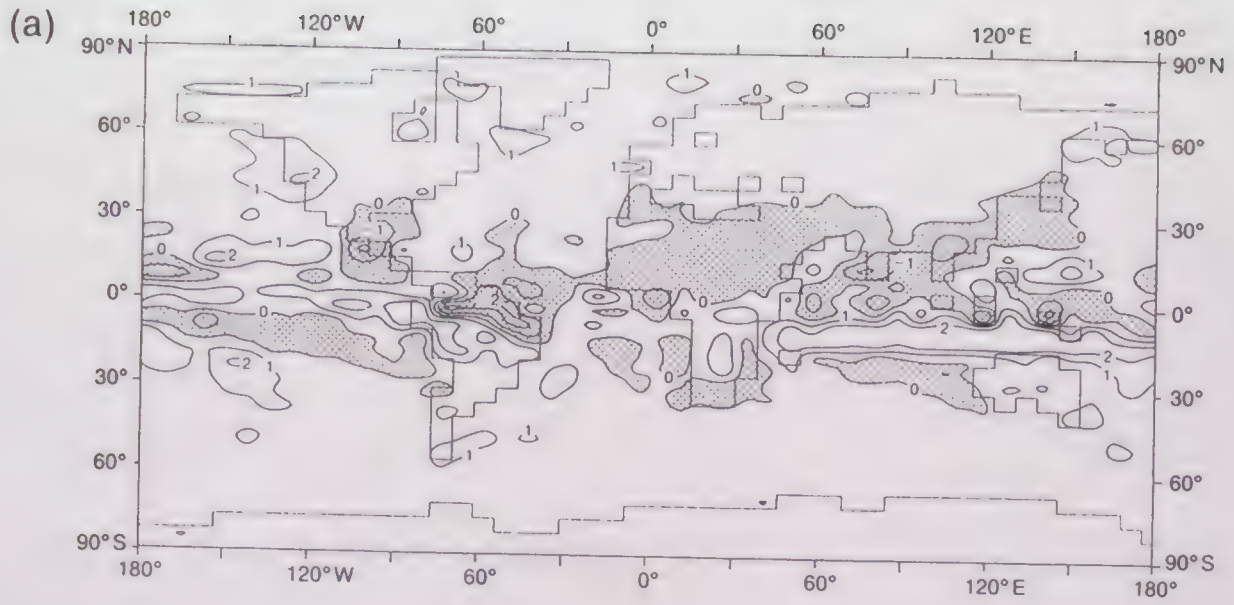

20
15
10
8
6
4
2
0
% increase in precipitation
Clausius–Clapeyron
BMO
M1
GISS
GFDL
OSU
NCAR
M2
M3
1
2
3
4
5
6
Change in global mean surface temperature

FIGURE 5


(a)
180°
120°W
60°
0°
60°
120°E
180°
90°N
60°
30°
0°
30°
60°
90°S

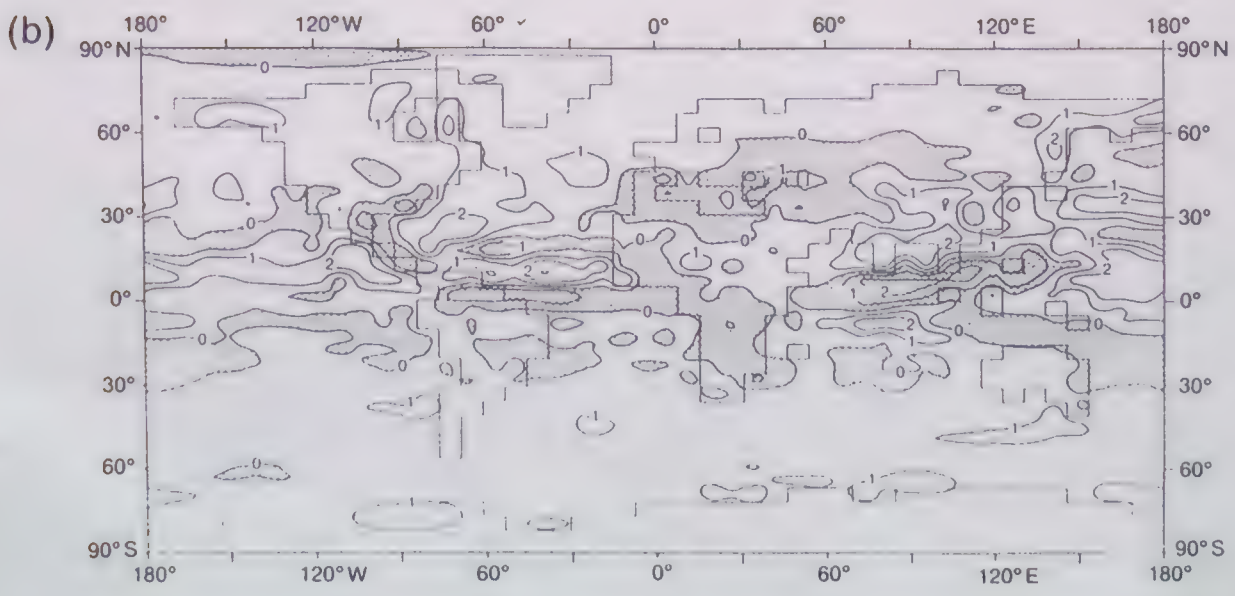

(b)
180°
120°W
60°
0°
60°
120°E
180°
90°N
60°
30°
0°
30°
60°
90°S

FIGURE 6

SOIL WATER DIFFERENCES FOR JJA

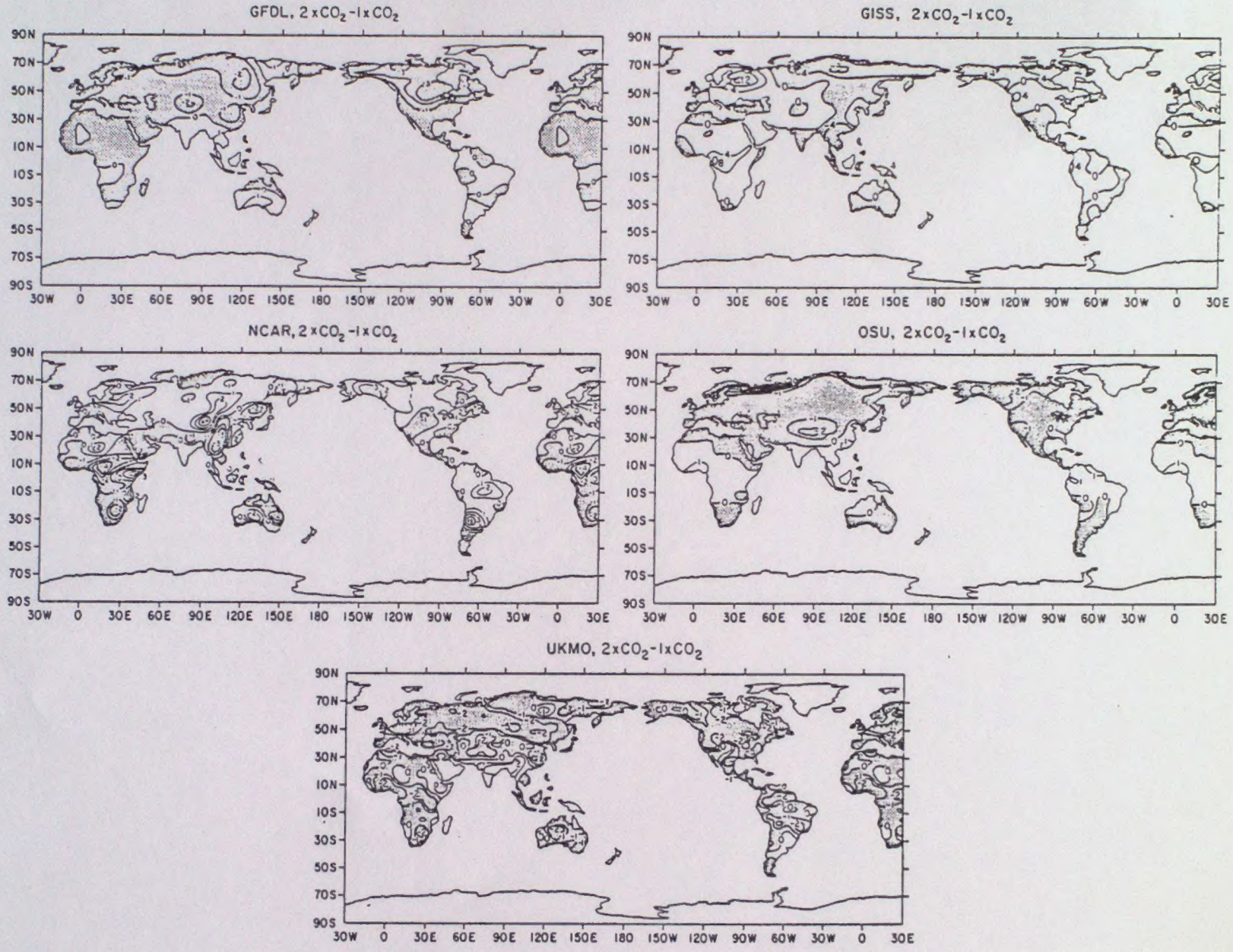


FIGURE 7

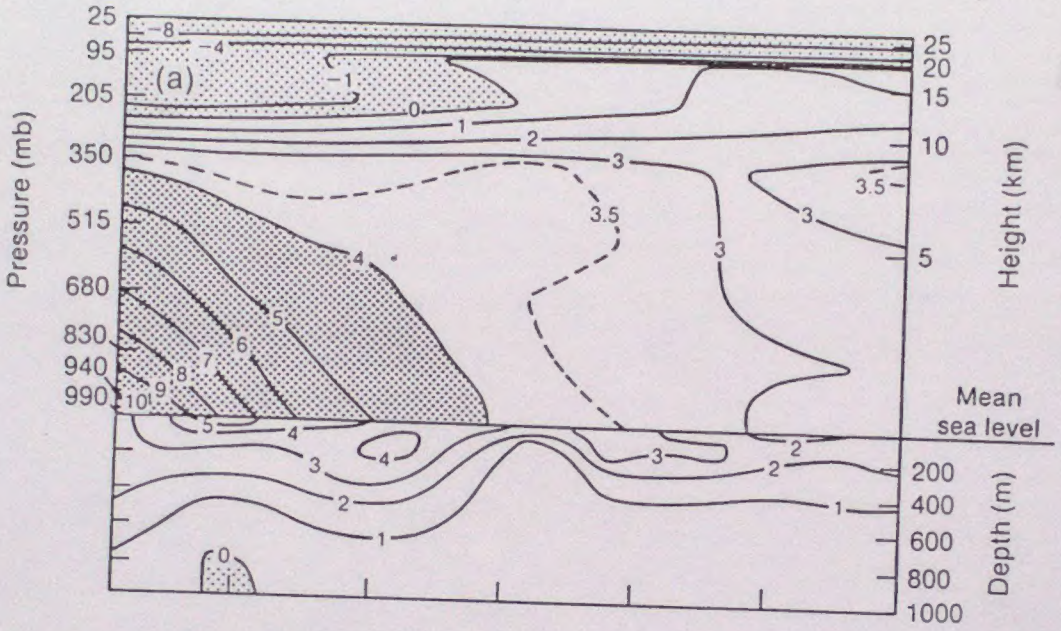

25
95
205
350
515
680
830
940
990
Pressure (mb)
(a)
25
20
15
10
5
Height (km)
Mean
sea level
200
400
600
800
1000
Depth (m)

FIGURE 8

DYNAMICAL CLIMATOLOGY TECHNICAL NOTES

DCTN 1 June 1984
A scheme for incorporating the thermodynamic sea-ice model into a coupled ocean-atmosphere model.
C Gordon and M Bottomley

DCTN 2 Sept 1984
The parametrization of the upper ocean mixed layer in coupled ocean/atmosphere models.
C Gordon and M Bottomley

DCTN 3 Sept 1984
The response of a simple thermodynamic sea-ice model to GCM forcing appropriate for perennial sea-ice.
M Bottomley

DCTN 4 Sept 1984
Potential vorticity in the stratosphere derived using data from satellites.
S A Clough, N S Grahame and A O'Neill

DCTN 5 Sept 1984
Simulation of the seasonal cycle of SST using globally specified climatological data to force simple ocean models.
N S Grahame

DCTN 6 Sept 1984
Development of an improved GCM radiation scheme.
A Slingo and R C Wilderspin

DCTN 7 Sept 1984
On the specification of surface fluxes in coupled atmosphere/ocean general circulation models.
J F B Mitchell, C A Wilson and C M Price

DCTN 8 Sept 1984
A survey of possible repercussions of the Soviet river reversal programme on Arctic sea-ice.
H Cattle

DCTN 9 Oct 1984
A study of a strong stratospheric warming during January 1982
T D A Fairlie

DCTN 10 Nov 1984
An intercomparison of the Met O 11 M45 model and the Met O 20 11-level model on the Cyber 205
J F Dyson

DCTN 11 Nov 1984
Simulation of observed time series of temperature and precipitation over eastern England.
D M Reed

DCTN 12 Nov 1984
Forecasts and analyses of the onset of the Southwest monsoon.
R Kershaw

DCTN 13 Nov 1984
On modelling the effects of CO_2 on climate.
J F B Mitchell

DCTN 14 Dec 1984
Development of a revised longwave radiation scheme for an atmospheric general circulation model.
A Slingo and R C Wilderspin

DCTN 15 Jan 1985
Rossby wavetrains in the stratosphere forced by localised disturbances in the troposphere.
C J Marks (Oxford), A O'Neill and V D Pope

DYNAMICAL CLIMATOLOGY TECHNICAL NOTES

DCTN 16 Jan 1985
Observing system experiments using the Meteorological Office's 15-level model.
M A Bromley

DCTN 17 Feb 1985
Atmospheric general circulation simulation of the climate of the Mediterranean region.
H Cattle

DCTN 18 Feb 1985
Diurnal variation and cloud in a general circulation model.
C A Wilson and J F B Mitchell

DCTN 19 Feb 1985
The sensitivity of the Saharan region in a general circulation model.
W M Cunnington and P R Rowntree

DCTN 20 Mar 1985
The impact of aircraft observations on analyses and forecasts from the operational 15-level model.
B R Barwell

DCTN 21 Mar 1985
Non-linear effects on heat-induced circulation of the tropical atmosphere.
A E Gill and P J Phlips

DCTN 22 Apr 1985
Simulation of cloudiness with the U.K. Meteorological Office 11-layer AGCM.
A Slingo and R C Wilderspin

DCTN 23 Apr 1985
An integrated approach to the representation of cloud processes. R N B Smith

DCTN 24 May 1985
Nuclear Winter: Calculations of the shortwave radiative effects of soot aerosols.
A Slingo and P Goldsmith

DCTN 25 Jul 1985
Sea ice and the Antarctic winter circulation: a numerical experiment.
J F B Mitchell and T S Hills

DCTN 26 Jul 1985
A Budyko-Sellers model for study of ocean-atmosphere interaction.
W J Ingram

DCTN 27 Aug 1985
The effect of a shoaling thermocline on equatorially-trapped Kelvin waves.
A E Gill and B A King

DCTN 28 Sept 1985
CO_2 climate sensitivity and model dependence of results.
J F B Mitchell, C A Wilson and W M Cunnington

DCTN 29 Sept 1985
Handbook of the Meteorological Office 11-layer atmospheric general circulation model.
Volume 1 : Model Description
Edited by A Slingo

DCTN 30 Sept 1985
Impact of land surface variations on African rainfall in general circulation models.
P R Rowntree, M F Wilson and A B Sangster

DCTN 61 Jan 1988 — Early winter in the northern stratosphere.
M N Juckes and A O'Neill

DCTN 62 Feb 1988 — Single column model tests of the Rowntree convection scheme using GATE data.
D Gregory

DCTN 63 Mar 1988 — The antarctic winter; simulations with climatological and reduced sea-ice extents.
J F B Mitchell and C A Senior

DCTN 64 Mar 1988 — An investigation of the Gates asynchronous coupling strategy using a simple energy-balance model.
D L Roberts

DCTN 65 Apr 1988 — The effect of improved physical parametrizations on simulations of cloudiness and the earth's radiation budget.
A Slingo, R C Wilderspin and R N B Smith

DCTN 66 May 1988 — Comparison of data and derived quantities for the middle atmosphere of the southern hemisphere.
W L Grose and A O'Neill

DCTN 67 Aug 1988 — Progress and future developments in modelling the climate system with general circulation models.
P R Rowntree

DCTN 68 Aug 1988 — A scheme for predicting layer clouds and their water content in a general circulation model.
R N B Smith

DCTN 69 Nov 1988 — Modelling climate change: an assessment of sea-ice and surface albedo feedbacks.
W J Ingram, C A Wilson and J F B Mitchell

DCTN 70 Dec 1988 — The "greenhouse" effect and climate change
J F B Mitchell

DCTN 71 Dec 1988 — On the dependence of climate sensitivity on convective parametrization.
W M Cunnington and J F B Mitchell

DCTN 72 Dec 1988 — Land surface parametrizations - basic concepts and review of schemes.
P R Rowntree

DCTN 73 Jan 1989 — Climate sensitivity: model dependence of results.
J F B Mitchell

DCTN 74 Jan 1989 — Parametrization of the upper ocean mixed layer in a tropical ocean GCM.
S Ineson and C Gordon

DCTN 75 Mar 1989 — A simple tropical coupled ocean-atmosphere model.
G R Budin and M K Davey

DYNAMICAL CLIMATOLOGY TECHNICAL NOTES

DCTN 76 Jun 1989 — The needs of general circulation models for runoff data.
P R Rowntree

DCTN 77 Jul 1989 — General circulation modelling of the atmosphere.
J F B Mitchell

DCTN 78 Jul 1989 — A model simulation of the seasonal cycle in the tropical Pacific Ocean using climatological and modelled surface forcing.
C Gordon and R A Corry

DCTN 79 Jul 1989 — Climatic impact of Amazon deforestation.
J Lean and D A Warrilow

DCTN 80 Sept 1989 — Surface evaporation during free convection.
C Gordon and D L Hunt

DCTN 81 Sept 1989 — A mass flux convection scheme with representation of cloud ensemble characteristics and stability dependent closure.
D Gregory and P R Rowntree